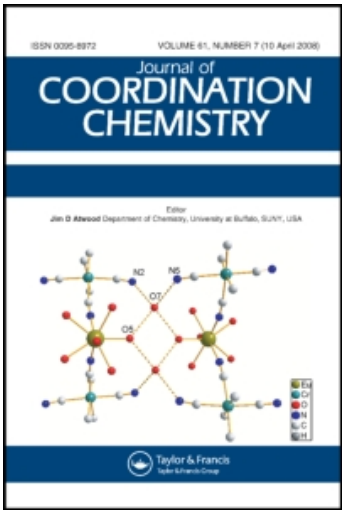


Journal of Coordination Chemistry
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713455674

NMR and FTIR studies of coordinate-bonding and intramolecular and intermolecular hydrogen bonding in zinc(II)(3,5-diisopropylsalicylate)$_2$

Gegham Z. Sedrakyan[a]; Frederick E. Evans[b]; Seyran H. Minasyan[a]; Levon A. Tavadyan[a]; Grant W. Wangila[c]; Richard B. Walker[c]; John R. J. Sorenson[c]
[a] Institute of Chemical Physics, National Academy of Sciences, Yerevan 0014, Armenia [b] Division of Chemistry, National Center for Toxicological Research, Jefferson, Arkansas, 72079, USA [c] Department of Chemistry and Physics, University of Arkansas at Pine Bluff, Pine Bluff, Arkansas 71601, USA

First published on: 22 September 2010

To cite this Article Sedrakyan, Gegham Z. , Evans, Frederick E. , Minasyan, Seyran H. , Tavadyan, Levon A. , Wangila, Grant W. , Walker, Richard B. and Sorenson, John R. J.(2008) 'NMR and FTIR studies of coordinate-bonding and intramolecular and intermolecular hydrogen bonding in zinc(II)(3,5-diisopropylsalicylate)$_2$', Journal of Coordination Chemistry, 61: 18, 2861 — 2875, First published on: 22 September 2010 (iFirst)
To link to this Article: DOI: 10.1080/00958970802087086
URL: http://dx.doi.org/10.1080/00958970802087086

Journal of Coordination Chemistry
Vol. 61, No. 18, 20 September 2008, 2861–2875

NMR and FTIR studies of coordinate-bonding and intramolecular and intermolecular hydrogen bonding in zinc(II)(3,5-diisopropylsalicylate)$_2$

GEGHAM Z. SEDRAKYAN†, FREDERICK E. EVANS‡, SEYRAN H. MINASYAN†, LEVON A. TAVADYAN*†, GRANT W. WANGILA§, RICHARD B. WALKER§ and JOHN R. J. SORENSON§¶

†Institute of Chemical Physics, National Academy of Sciences, Republic of Armenia, 5/2, P. Sevak Street, Yerevan 0014, Armenia
‡Division of Chemistry, National Center for Toxicological Research, Jefferson, Arkansas, 72079, USA
§Department of Chemistry and Physics, University of Arkansas at Pine Bluff, 1200 North University Avenue, Pine Bluff, Arkansas 71601, USA
¶Department of Pharmaceutical Sciences, College of Pharmacy, Division of Medicinal Chemistry, University of Arkansas for Medical Sciences, 4301 West Markham Street, Little Rock, Arkansas 72205-7122, USA

(*Received 22 January 2008; in final form 24 January 2008*)

Carboxylate and salicylic OH coordinate bonding as well as intramolecular and intermolecular hydrogen bonding of *bis*-3,5-diisopropylsalicylatozinc(II), [Zn^{II}(3,5-DIPS)$_2$], with Lewis bases were studied to determine mechanisms accounting for antioxidant reactivity of Zn^{II}(3,5-DIPS)$_2$. Apparent thermodynamic parameters: K_{eq}, ΔS^0, ΔH^0, and ΔG^0 were determined for these equilibria with bonding of two molecules of dimethyl sulfoxide-d_6 (DMSO) or ethyl acetate-d_8 (EA) to the Zn^{II} using NMR and FTIR. We conclude that addition of two equivalents of DMSO or EA to non-polar solutions of Zn^{II}(3,5-DIPS)$_2$ results in bonding of DMSO or EA to Zn^{II} via sulfoxide or ester carbonyl oxygen atoms with ternary complex formation, leading to weakening of carboxylate and salicylic OH coordinate bonding to Zn^{II} and strengthening intramolecular hydrogen bonding between protons of salicylic OH groups and carboxylate oxygens. Subsequent addition of two or three additional equivalents of DMSO or EA leads to intermolecular hydrogen bonding between protons of salicylic OH groups.

Keywords: *Bis*-3,5-diisopropylsalicylatozinc(II); NMR; FTIR; Coordinate bonding; Intramolecular and intermolecular hydrogen bonding

1. Introduction

The lipophilic complex *bis*-3,5-diisopropylsalicylatozinc(II), [Zn^{II}(3,5-DIPS)$_2$], and its solvates demonstrated anticonvulsant activity [1, 2] as well as radioprotective and

*Corresponding author. Email: tavadyan@ichph.sci.am

ISSN 0095-8972 print/ISSN 1029-0389 online © 2008 Taylor & Francis
DOI: 10.1080/00958970802087086

radiorecovery activities in animal models [1, 3]. It was also found to have antioxidant reactivity with a capacity to react with, and remove, tertbutylperoxyl radical, preventing peroxyl radical mediated oxidation of alkyl substituted aromatic hydrocarbons [4]. The observed biological activity of $Zn^{II}(3,5\text{-DIPS})_2$ may be related, at least in part, to its ability to react with peroxyl radicals generated *in vivo*.

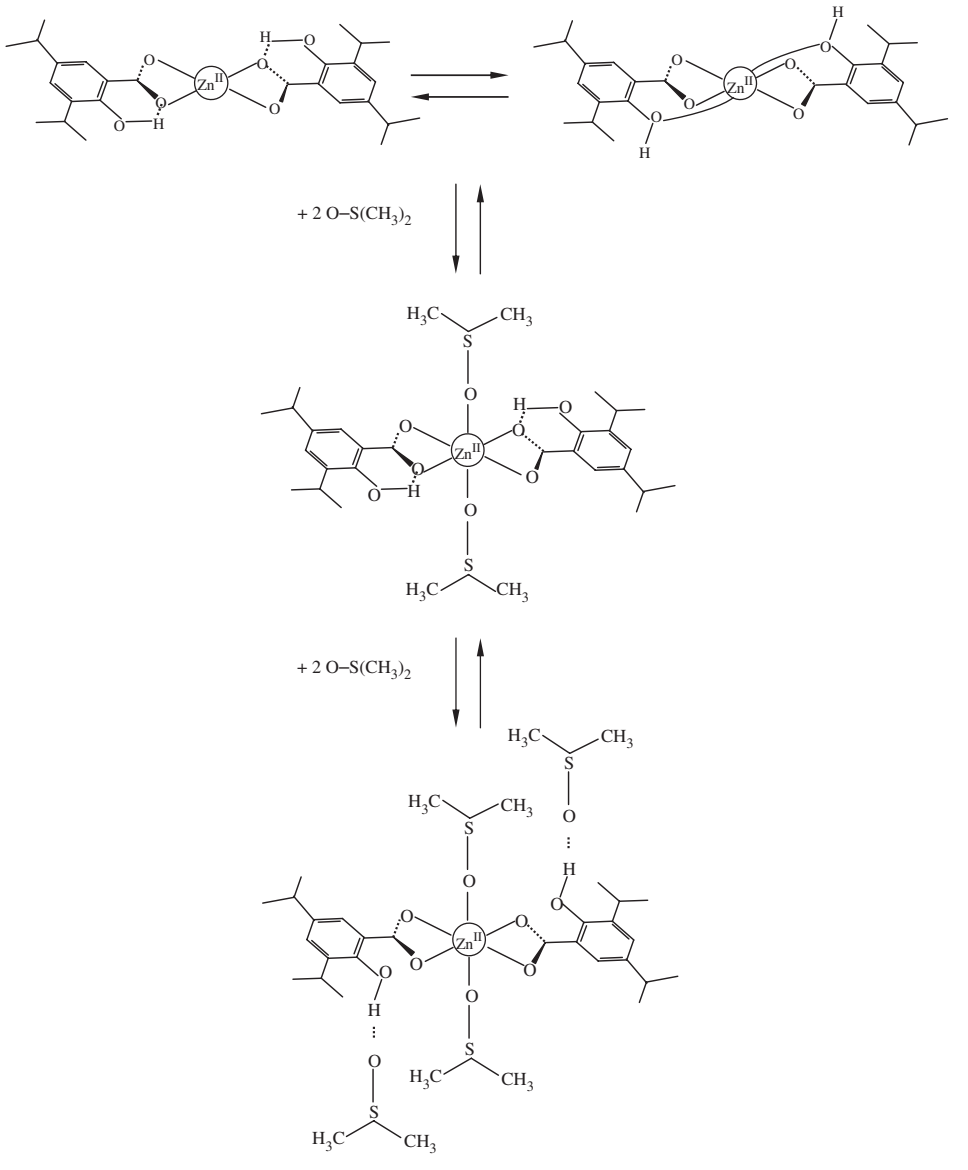
The X-ray crystal structure of $Zn^{II}(3,5\text{-DIPS})_2$ has been determined [5]. Using NMR, FTIR and kinetic EPR methods it was subsequently established that the reaction center for antiperoxyl radical reactivity was the salicylic OH protons of the 3,5-DIPS ligands. Addition of solvating ligands such as ethyl acetate or amyl acetate, which contain a Lewis base functional group with non-bonded valence electrons capable of forming ternary complexes via axial bonding to the Zn^{II} atom in $Zn^{II}(3,5\text{-DIPS})_2$ chelates, and formation of intermolecular hydrogen bonds with salicylic OH protons decreased antiperoxyl radical reactivity of $Zn^{II}(3,5\text{-DIPS})_2$ as well as Cu^{II} and Fe^{III} 3,5-DIPS metallochelates [4, 6, 7]. This observation suggested that the decrease in antiperoxyl radical reactivity was due to the ultimate formation of intermolecular hydrogen bonds with the Lewis base carbonyl oxygen of ethyl or amyl acetate and protons of the salicylic hydroxyl groups of the 3,5-DIPS ligands [4, 6, 7]. This influence of intermolecular hydrogen bonding in decreasing antiradical antioxidant reactivity has been reported in detail [8–14] including mechanistic processes involved in elementary reactions of antioxidant phenolic compounds with peroxyl [8, 9] and alkoxyl [10, 11] radicals in various media [10–14].

As shown at the top of scheme 1 the predominant form of $Zn^{II}(3,5\text{-DIPS})_2$ in a non-polar solvent is a mononuclear chelate with oxygens of carboxylate and salicylic OH groups coordinated to Zn^{II}. Under these conditions the chelate exists in two forms in equilibrium, as shown in scheme 1. In the first form the chelate exists with an intramolecular hydrogen bond wherein salicylic OH protons are hydrogen bonded to carboxylate oxygen atoms. In the second form oxygen of phenolic OH group is in a comparatively non-bonded state.

The intramolecular and intermolecular hydrogen bonded forms are in dynamic equilibrium in non-polar solvents as shown for $Zn^{II}(3,5\text{-DIPS})_2$ and for substituted Cu^{II} salicylates using differential pulse and cyclic voltammetry methods, which allow distinguishing salicylic OH groups with readily available protons from those involved in intramolecular hydrogen bonding [4, and unpublished results].

The influence of Lewis base electron-donor compounds on antiradical reactivity of metallochelates is more complicated due to the presence of electron-donor–acceptor bonding centers, also shown in scheme 1. Sequential addition of DMSO to a CD_2Cl_2 solution of $Zn^{II}(3,5\text{-DIPS})_2$ was found to lead to sequential increase in chemical shift for salicylic OH protons.

As shown in scheme 1, in the second form the hydroxyl protons are readily accessible as sites for hydrogen abstraction reactions, required for antiradical antioxidant reactivity in lipido-mimetic media, while protons of the intramolecular hydrogen bonded form are less accessible and less reactive in hydrogen abstraction reactions. However, this intramolecular hydrogen bonding interaction becomes stronger and predominates following addition of a Lewis base, as illustrated in scheme 1. With addition of DMSO there is an anticipated weakening of the bonds formed between carboxylate oxygens and salicylate OH oxygen atoms with Zn^{II} resulting in an increase in electron density on these oxygens. This increase in electron density on carboxylate and salicylate oxygens, while increasing the strength of salicylate O–H bond places



Scheme 1. Coordinate-covalent bonding interactions in $Zn^{II}(3,5\text{-DIPS})_2$ and hydrogen bonding interactions with addition of dimethyl sulfoxide.

carboxylate oxygen atoms with high electron density in the vicinity of salicylate OH protons and leads to formation of an intramolecular hydrogen bond, as shown in scheme 1.

An initial axial bonding of two equivalents of Lewis base initiates two processes in sequence: (1) weakening of coordinate bonding between oxygen of the carboxylic and salicylic OH groups and Zn^{II} and (2) formation and strengthening of intramolecular hydrogen bonding interactions between carboxylate oxygens and salicylic OH protons of 3,5-DIPS ligands. With a further increase in concentration of Lewis base there

is a weakening of this intramolecular hydrogen bonding interaction in $Zn^{II}(3,5\text{-DIPS})_2$ resulting in formation of intermolecular hydrogen bonds between salicylic OH protons of 3,5-DIPS ligands and Lewis base non-bonding valence electrons.

To better understand the mechanistic influence of Lewis bases on antiradical reactivity of metallochelates, it was necessary to take into account the multifaceted nature of this influence. In so doing, it was necessary to consider possible interactions for this class of antioxidants as represented by $Zn^{II}(3,5\text{-DIPS})_2$: (1) equilibria for bonding interaction between a solvating ternary ligand and Zn^{II}, (2) equilibria for bonding interaction of carboxylate oxygen atoms with Zn^{II}, (3) equilibria for bonding interaction of salicylic OH oxygen atoms with Zn^{II}, (4) equilibria for bonding interactions leading to intramolecular hydrogen bonding between salicylic OH protons and carboxylate oxygen, and (5) equilibria for intermolecular hydrogen bonding interactions between a Lewis base and salicylate OH protons.

The objective was to study, in lipophilic medium, details of bonding interactions between Lewis bases and metallochelates wherein the ligand contains a salicylic OH. These studies were performed using NMR and FTIR spectroscopy using $Zn^{II}(3,5\text{-DIPS})_2$. Bonding interactions involving Zn^{II} and intramolecular and intermolecular hydrogen bonding interactions, shown in scheme 1, can influence antioxidant reactivity and account for the decreased antioxidant reactivity of $Zn^{II}(3,5\text{-DIPS})_2$ in the presence of Lewis bases. These bonding interactions may also have a role in the pharmacological activities of this and other essential metalloelement salicylate chelates.

2. Experimental

2.1. *Materials*

Ethyl acetate-d_8 (99.5 atom % deuterium) (EA) and chloroform-d_1 (99.9 atom % deuterium) (CCl_4) were purchased from Sigma Aldrich. Methylene chloride-d_2 (99.9 atom % deuterium) (CD_2Cl_2) and dimethyl sulfoxide-d_6 (99.9 atom % deuterium) (DMSO) were purchased from Cambridge Isotope Laboratories.

Dimethyl sulfoxide, EA, and carbon tetrachloride (CCl_4) (all from Aldrich) were used as purchased or purified according to known procedures [14]. Before carbon tetrachloride was used it was passed over a column of activated Al_2O_3. 3,5-Diisopropylsalicylic (3,5-diisopropylsalicylic) acid (3,5-DIPS acid) (Hochem Enterprises, Inc., Houston, Texas) was used without further purification. *Bis*-3,5-diisopropylsalicylatozinc(II) was synthesized as described [1]. The hydrate was dried at 323 K and 15 mm Hg for 16 h before it was used to obtain NMR spectra, which did not reveal water of hydration.

2.2. *Apparatus and measurements*

A Brüker 500 MHz instrument was used to obtain NMR spectra. The precision of measured chemical shifts was ± 0.02 Hz.

The 4000 to 400 cm^{-1} Fourier transform infrared (FTIR) spectra were recorded with a Nicolet FTIR Nexus spectrometer, for 32 scans and a resolution of $\pm 2\,cm^{-1}$, using 0.0625 mm KBr discs for solid samples or CCl_4 solutions.

2.2.1. NMR spectra. Stock solutions of 0.0369 M $Zn^{II}(3,5\text{-DIPS})_2$ were prepared in chloroform-d_1 or methylene chloride-d_2. The stock 0.0738 M 3,5-DIPS acid solution was prepared in chloroform-d_1. A volume of 0.8 ml of these solutions was placed in 528PP Wilmad NMR tubes and capped. The NMR spectra were recorded for these solutions following successive additions of 2 μL of dimethyl sulfoxide-d_6 (DMSO) or ethyl acetate-d_8 (EA) at temperatures ranging from 243 to 323 K. A temperature of 303 K was used to examine interactions of DMSO with 3,5-DIPS acid. The accuracy of temperature measurements was ± 0.2 K. NMR spectra were recorded 20 to 25 min after addition of each 2 μL of Lewis base and mixing by diffusion and equilibration. The total increase in volume with these additions was no more than 2%.

2.2.2. FTIR spectra. Stock solutions of 0.0369 M $Zn^{II}(3,5\text{-DIPS})_2$ and 0.0738 M 3,5-DIPS acid were prepared in CCl_4. These solutions were used to fill 2 ml Eppendorf tubes in a nitrogen-filled dry bag. Each tube was fitted with a tight-fitting cap and wrapped with parafilm to prevent evaporation. The FTIR spectra were recorded following addition of 1.5 μL of DMSO or EA to the solution of $Zn^{II}(3,5\text{-DIPS})_2$ or 3,5-DIPS acid. Solutions of 10 to 12 different molar concentration ratios, varying from 0 to 0.74 M EA and DMSO, were studied. FTIR spectra were recorded 20 to 25 min after each addition of Lewis base to allow mixing by diffusion and equilibration to examine interactions of DMSO or EA with $Zn^{II}(3,5\text{-DIPS})_2$ and 3,5-DIPS acid at 297 K. The accuracy of temperature measurements was ±0.5 K.

2.3. *Determinations of thermodynamic parameters for interactions of $Zn^{II}(3,5\text{-DIPS})_2$ with Lewis bases [16–19]*

Equilibria involved in interactions between Zn(II)(3,5-DIPS)$_2$ and DMSO or EA were calculated following measurement of the equilibrium constant, K_{eq}, for the equilibrium: $Zn^{II}(3,5\text{-DIPS})_2$ [A] + [D] $\rightleftarrows$ ($Zn^{II}(3,5\text{-DIPS})_2$)(Lewis base)$_{1-2}$ [AD], $K_{eq} = [AD]/[A][D]$ as a function of temperature. Here, [A] is the molar concentration of $Zn^{II}(3,5\text{-DIPS})_2$ and [D] is the molar concentration of available Lewis base, while [AD] is the molar concentration of [$Zn^{II}(3,5\text{-DIPS})_2$(Lewis base)] complex formed.

An equilibrium for bonding of only two molecules of Lewis base to $Zn^{II}(3,5\text{-DIPS})_2$ was considered (scheme 1). In this case only formation of intramolecular hydrogen bonds was examined. We consider the nature of Lewis base bonding to $Zn^{II}(3,5\text{-DIPS})_2$ to be equivalent and no change in ability of the intermediate chelate to coordinate the second molecule of Lewis base in the presence of the first molecule.

The chemical shift observed for A, assuming rapid equilibrium between A and AD, is the weighted mole fraction average of the chemical shift for A, δ^0_A, and AD complex, δ^0_{AD} [16–19]. With this assumption the above equilibrium gives:

$$K_{eq} = \frac{\Delta\delta_{obsd}}{\left(\Delta\delta^0_{AD} - \Delta\delta_{obsd}\right)}\left\{\left[D^0\right] - \left(\frac{\Delta\delta_{obsd}\left[A^0\right]}{\Delta\delta^0_{AD}}\right)\right\}^{-1} \quad (1)$$

where [D^0] and [A^0] are initial concentrations of $Zn^{II}(3,5\text{-DIPS})_2$ and a Lewis base, $\Delta\delta_{obsd}$ is the difference between the observed chemical shift due to formation of the complex with the Lewis base and $Zn^{II}(3,5\text{-DIPS})_2$ or 3,5-DIPS acid and free $Zn^{II}(3,5\text{-DIPS})_2$ or 3,5-DIPS acid. $\Delta\delta_{obsd} = \delta_{obsd} - \Delta\delta^0_A$, $\Delta\delta^0_{AD}$ is the difference

between chemical shift for Zn^{II}(3,5-DIPS)$_2$(Lewis base) and Zn^{II}(3,5-DIPS)$_2$ or 3,5-DIPS acid, $\Delta\delta^0_{AD} = \delta^0_{AD} - \Delta\delta^0_A$, and [$A^0$] were calculated based upon the presence of two 3,5-DIPS ligands in Zn^{II}(3,5-DIPS)$_2$ that interact with the Lewis base, which required doubling the concentration of 3,5-DIPS acid to obtain the same concentration of salicylic OH protons used in these calculations with the assumption that both reaction centers are equivalent.

To obtain equation (1) we considered values of chemical shifts for the two protons of the salicylic OH groups of 3,5-DIPS to be similarly intramolecularly hydrogen bonded. The dependence of changes in salicylic OH proton chemical shifts with ratios of [DMSO] : [Zn^{II}(3,5-DIPS)$_2$] of up to 2.5 : 1 and [EA] : [Zn^{II}(3,5-DIPS)$_2$] of up to 3.5 : 1 revealed the equilibrium process involved in bonding of two Lewis bases to Zn^{II}(3,5-DIPS)$_2$. Here we were guided not only by considerations for calculation of K_{eq}, but also by considerations involving the principal chemical shift changes for the salicylic OH protons from formation of Zn^{II}(3,5-DIPS)$_2$(Lewis base)$_2$.

By measuring $\Delta\delta_{obsd}$ at different concentrations of D°, K_{eq} and $\Delta\delta^0_{AD}$ were determined using equation (1). Calculations of these values were performed using regression analyses performed with the MATLAB 6.5 computer program. Changes in standard entropy (ΔS^0) and enthalpy (ΔH^0) for bonding of Lewis base molecules with Zn^{II}(3,5-DIPS)$_2$ were calculated using the vant Hoff equation:

$$\ln K_{eq} = \Delta S^0/R - \Delta H^0/RT \tag{2}$$

and the change in standard free energy (ΔG^0) was also calculated.

3. Results and discussion

3.1. *NMR studies*

NMR spectra for salicylic OH groups of Zn^{II}(3,5-DIPS)$_2$ in the absence or presence of various concentrations of Lewis bases with non-bonded valence electrons that serve as electron-donors, such as DMSO or EA, are presented in figure 1(a) and figure 1(b), respectively. Addition of two equivalents of Lewis base to a solution of Zn^{II}(3,5-DIPS)$_2$ leads to a marked increase in chemical shift for salicylic OH protons of Zn^{II}(3,5-DIPS)$_2$. These shifts are due to axial bonding of two equivalents of Lewis base via sulfoxide oxygen (DMSO) or carbonyl oxygen (EA) with Zn^{II}, which results in strengthening of intramolecular hydrogen bonding between protons of salicylic OH groups and carboxyl oxygen atoms of 3,5-DIPS. This phenomenon leads to a mediated kinetic medium effect. Ordinary kinetic medium effects in reaction of phenolic compounds with free radicals involve blocking of the reaction center by intermolecular hydrogen bonds between phenolic OH protons and Lewis base [8–13]. In the case of Zn^{II}(3,5-DIPS)$_2$ the Lewis base molecules undergo axial coordination with Zn^{II} atom which favors formation of stronger intramolecular hydrogen bonds between protons of salicylic OH and carboxyl oxygens of 3,5-DIPS, favoring decrease of antiradical reactivity of salicylic OH.

Subsequent addition of two to three equivalents of Lewis base to Zn^{II}(3,5-DIPS)$_2$ leads to a further but less pronounced increase in chemical shift due to weakening of the intramolecular hydrogen bonding interaction with formation of intermolecular

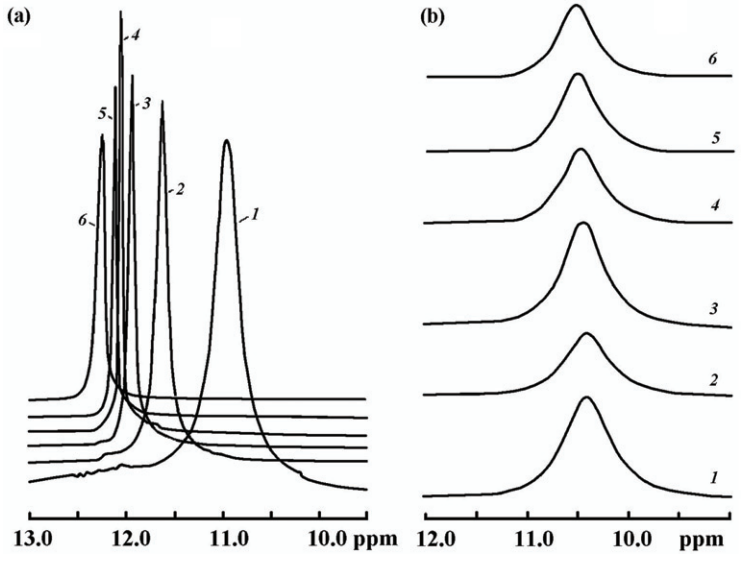


Figure 1. (a) Chemical shifts for salicylic OH protons following addition of 1, 0; 2, 0.0325; 3, 0.0625; 4, 0.0975; 5, 0.13; or 6, 0.1625 M DMSO at 243 K or (b) 1, 0; 2, 0.0249; 3, 0.0497; 4, 0.0746; 5, 0.0994; 6, 0.1243 M EA at 303 K to a CD_2Cl_2 solution of 0.0369 M $Zn^{II}(3,5\text{-DIPS})_2$.

hydrogen bonds between salicylic OH protons and sulfoxide or carbonyl oxygens of these Lewis bases.

With formation of hydrogen bonds, bond length and polarity of salicylic O–H bonds increase [13] leading to a decrease in electron density on the proton. However, at the same time there is a concomitant increase in electron transfer from the Lewis base oxygen of DMSO or EA to the proton of OH. The overall result is an exchange of the source of electron density on the proton and transformation of intramolecular hydrogen bonds to intermolecular hydrogen bonds, leading to a gradual increase in NMR chemical shift, as shown in figures 2 and 3, for salicylic OH protons of $Zn^{II}(3,5\text{-DIPS})_2$.

Sequential addition of DMSO to a CD_2Cl_2 solution of $Zn^{II}(3,5\text{-DIPS})_2$ led to an increase in chemical shift to higher frequencies, from 65 Hz to a maximum shift of 138 Hz, corresponding to a gradual increase in intermolecular hydrogen bond formation between salicylic OH with addition of an additional three to five equivalents of DMSO.

For comparison, chemical shift changes for salicylic OH protons of 3,5-DIPS acid following addition of up to two equivalents of DMSO to a $CDCl_3$ solution gave a maximum shift of 177 Hz for intramolecular hydrogen bonding and a shift of 63 Hz for intermolecular hydrogen bonded salicylic OH protons in $Zn^{II}(3,5\text{-DIPS})_2(DMSO)_2$ (scheme 1). Based upon this intermolecular hydrogen bonding interaction with addition of DMSO to non-polar solutions of 3,5-DIPS acid causing disruption of intramolecular hydrogen bonds, as shown in scheme 2, it was clear that similar NMR shifts for salicylic OH protons of $Zn^{II}(3,5\text{-DIPS})_2$ were due to formation of intermolecular hydrogen bonds following addition of DMSO, consistent with the suggested structure shown in scheme 1.

With excess DMSO the maximum chemical shift for 3,5-DIPS acid and $Zn^{II}(3,5\text{-DIPS})_2$ in benzene-d_6 were 11.95 and 11.91 ppm, respectively, at 303 K (unpublished observation), similar to data reported by Lemoine *et al.* [20], who found the magnitude of proton chemical shift for salicylic OH protons in $Zn^{II}(3,5\text{-DIPS})_2(L)_n$

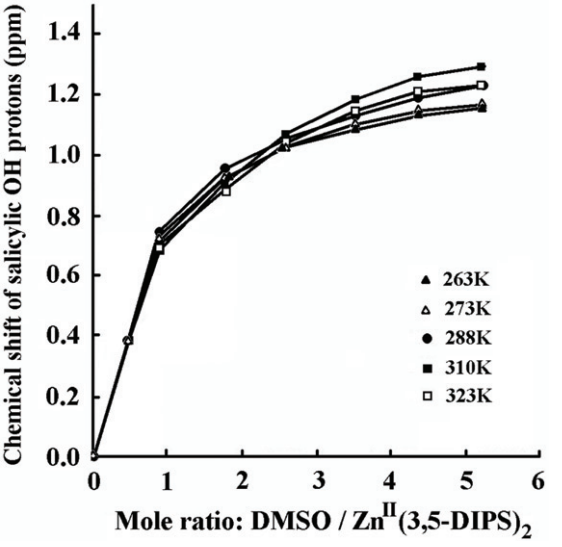


Figure 2. Observed chemical shift changes ($\Delta\delta_{obsd}$) for salicylic OH protons in 0.0369 M $Zn^{II}(3,5\text{-DIPS})_2$ $CDCl_3$ solutions contaning varying DMSO : $Zn^{II}(3,5\text{-DIPS})_2$ mole ratios at various temperatures.

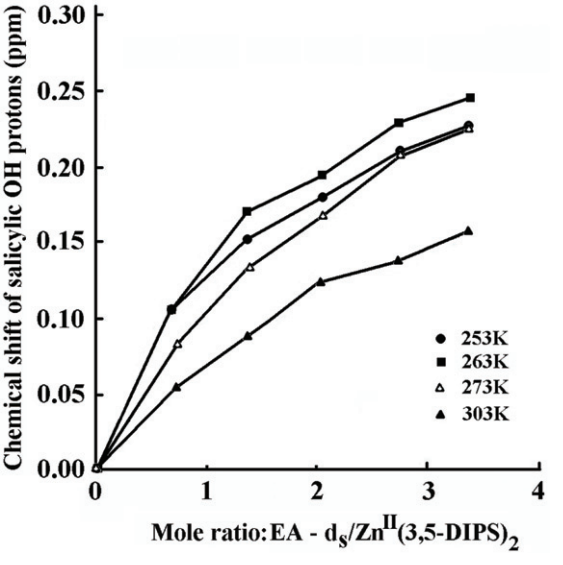


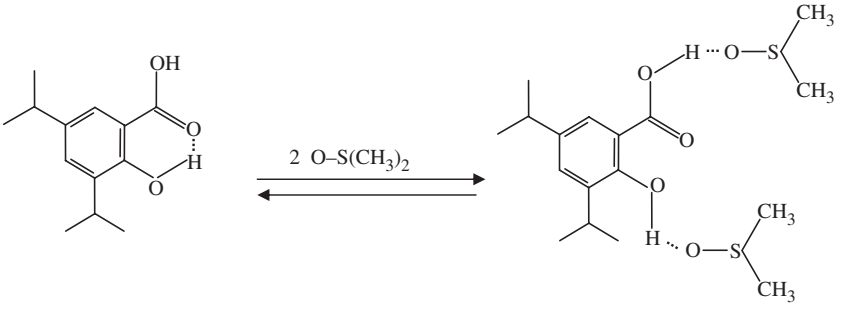
Figure 3. Observed chemical shifts ($\Delta\delta_{obsd}$) for salicylic OH protons in 0.0369 M $Zn^{II}(3,5\text{-DIPS})_2CD_2Cl_2$ solutions containing varying EA : $Zn^{II}(3,5\text{-DIPS})_2$ mole ratios at various temperatures.

increased with increase in basicity of axial ligands (L), as shown in table 1. The comparatively small change in chemical shift of 1.2–1.5 ppm observed during formation of hydrogen bonds arises from weak intramolecular hydrogen bonding of salicylic OH protons of $Zn^{II}(3,5\text{-DIPS})_2$, as shown in scheme 1. The similarity in intermolecular hydrogen bonding was also supported by essentially the same decrease in line width for salicylic OH protons of 3,5-DIPS acid and $Zn^{II}(3,5\text{-DIPS})_2$ obtained in benzene-d_6 (177 to 63 Hz and from 138 to 65 Hz, respectively), due to acceleration of chemical exchange of salicylic OH protons by hydrogen bonding [17–19].

With addition of an additional three to five equivalents of DMSO there was a weakening of intramolecular hydrogen bonds in $Zn^{II}(3,5\text{-DIPS})_2(DMSO)_2$ and formation of more intermolecular hydrogen bonds resulting in formation of $Zn^{II}(3,5\text{-DIPS})_2(DMSO)_4$. These interactions resulted in further increase in chemical shift for salicylic OH groups, as shown in figure 2.

The maximum chemical shift for protons of salicylic OH groups during addition of EA to a non-polar solution of $Zn^{II}(3,5\text{-DIPS})_2$ was achieved at a slightly higher molar concentration ratio of about 3.5 : 1 for EA : $Zn^{II}(3,5\text{-DIPS})_2$, as shown in figure 3. Moreover, smaller values of $\Delta\delta^0$ for the experimentally observed maximum value of chemical shift and for the calculated value $\Delta\delta^0_{AD}$ for this complex were observed, due to weaker basicity of EA.

Using equation (1), values for K_{eq} and $\Delta\delta^0_{obsd}$ were determined and ΔS^0, ΔH^0 and ΔG^0 were calculated (table 2). These parameters represent overall values for the multistage processes involved in transition from $Zn^{II}(3,5\text{-DIPS})_2$ to $Zn^{II}(3,5\text{-DIPS})_2(DMSO)_2$ or $Zn^{II}(3,5\text{-DIPS})_2(DMSO)_4$ with sequential addition of Lewis base to non-polar solutions of $Zn^{II}(3,5\text{-DIPS})_2$ and are attributed to the



Scheme 2. Intermolecular hydrogen bonding interactions of carboxylic acid and salicylic OH groups of 3,5-DIPS acid with dimethyl sulfoxide.

Table 1. NMR chemical shifts for salicylic OH protons of $Zn^{II}(3,5\text{-DIPS})_2(L)_n$ in CCl_4.

(L)*n*	None	$(EA)_2$	$(DMSO)_2$	1,10-phenanthroline	2,9-dimethyl-1, 10-phenanthroline
δ_{obsd} (ppm)	10.45	11.59	11.26[a] 11.48	11.92[a]	11.94[a]

[a]Data from [19].

Table 2. Chemical shifts and thermodynamic parameters: K_{eq}, ΔG^0, ΔH^0, and ΔS^0.

n	Ligand (solvent)	Temp. (K)	$\Delta\delta^0_{AD}$	K_{eq} (M^{-1})	ΔG^0, (cal mol^{-1})	ΔH^0, (cal mol^{-1})	ΔS^0, (cal(mol K)$^{-1}$)
1	DMSO ($CDCl_3$)	263	1.16 ± 0.04	37.34 ± 2.51	-1891 ± 34		
2		273	1.17 ± 0.04	34.49 ± 2.30	-1920 ± 34		
3		288	1.23 ± 0.05	30.62 ± 2.11	-1957 ± 38	-1701 ± 92	0.76 ± 0.32
4		310	1.29 ± 0.05	22.42 ± 1.82	-1915 ± 48		
5		323	1.23 ± 0.04	20.66 ± 1.50	-1942 ± 45		
6	EA (CD_2Cl_2)	253	0.25 ± 0.02	20.60 ± 1.44	-1520 ± 34		
7		263	0.26 ± 0.02	16.19 ± 1.25	-1454 ± 39	-3580 ± 775	-8.37 ± 2.87
8		273	0.25 ± 0.02	9.26 ± 0.72	-1206 ± 41		
9		303	0.18 ± 0.02	6.01 ± 0.42	-1079 ± 41		

overall process of hydrogen bond formation involving salicylic OH groups of 3,5-DIPS ligands (scheme 1). K_{eq} values increase with increase in basicity of the Lewis base. The basicity descriptor (B) of Koppel and Palm [21] are 193 for DMSO and 120 for EA while SB of Catalan [22] are 0.647 for DMSO and 0.542 for EA.

The larger the K_{eq} value, the larger the $\Delta\delta^0_{obsd}$ value, supporting increasing basicity of donor ligand increasing K_{eq} and also an increase in intramolecular hydrogen bonds. There is no correlation of K_{eq} and ΔH^0 values, consistent with an earlier report [19] on intermolecular hydrogen bonding or remaining thermodynamic parameters. Low values of ΔS^0, ΔH^0 and ΔG^0 indicate two processes: an exothermic process with the loss of entropy associated with dative bonding of a Lewis base with Zn^{II} and an endothermic process occurring with increase in entropy due to weakening of bonding of salicylic OH with Zn^{II} and intramolecular hydrogen bond formation.

3.2. *FTIR studies*

FTIR spectra support the conversion of relatively strong bonding between carboxylate oxygens and Zn^{II} in Zn^{II}(3,5-DIPS)$_2$, in the absence of DMSO to weaker bonds permitting intramolecular hydrogen bonding of salicylic OH with carboxylate oxygens and further interactions with DMSO involving intermolecular hydrogen bonds with increasing concentration of DMSO.

As shown in figure 4 increasing concentration of DMSO to CCl_4 solutions of Zn^{II}(3,5-DIPS)$_2$ resulted in a shift of the anti-symmetric carboxylate, ν_aCOO, stretching frequency observed at 1560 cm^{-1} for Zn^{II}(3,5-DIPS)$_2$ to a higher frequency (1585 cm^{-1}) as a result of gradual addition of two equivalents of DMSO, consistent with weakening of the bond of carboxylate to Zn^{II}. The maximum shift was achieved at a concentration ratio for DMSO : Zn^{II}(3,5-DIPS)$_2$ of 2 : 1. The IR absorbance shift for ν_aCOO on increasing concentration of DMSO attests to the non-equivalence of this shift due to intramolecular hydrogen bonding with initial axial bonding of the first equivalent of DMSO to the Zn^{II} and a further smaller shift with axial bonding of the second equivalent. Subsequently, an additional shift occurred with formation of intermolecular hydrogen bonds with an additional two equivalents of DMSO.

As shown in figures 4 and 5 addition of DMSO to non-polar solutions of Zn^{II}(3,5-DIPS)$_2$ caused a shift for the O–H stretching frequency of coordinated salicylic OH from 3240 cm^{-1} to 3100 cm^{-1} with successive additions of two equivalents of DMSO,

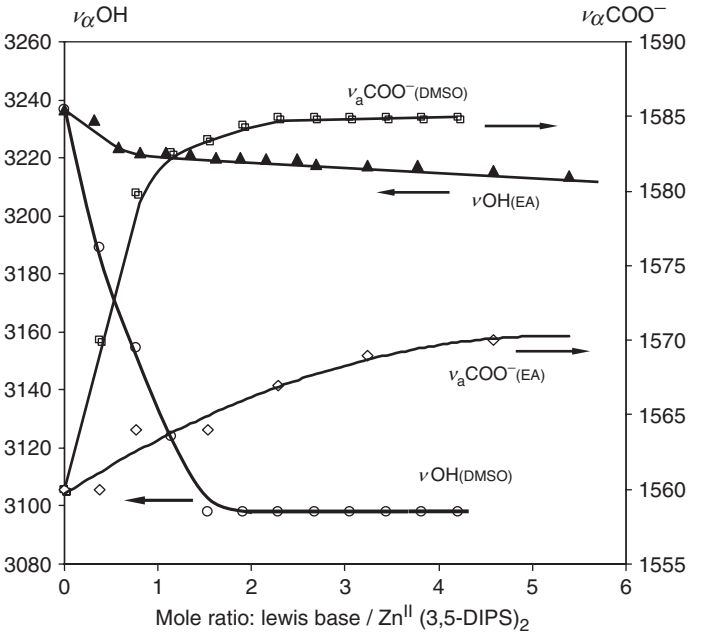


Figure 4. Frequency changes for OH and C=O absorbances in FTIR spectra at 24°C for 0.0369 M CCl_4 solutions of $Zn^{II}(3,5\text{-DIPS})_2$ containing varying DMSO : $Zn^{II}(3,5\text{-DIPS})_2$ mole ratios.

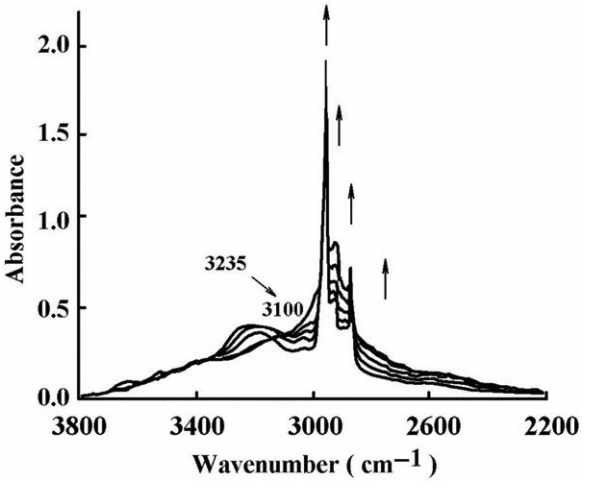


Figure 5. FTIR spectral changes through the range of 2200 to 3800 cm^{-1} at 24°C for 0.0369 M CCl_4 solutions of $Zn^{II}(3,5\text{-DIPS})_2$ containing 0 to 0.1989 M DMSO.

consistent with transition from intramolecular to intermolecular hydrogen bonded salicylic OH groups. With this shift the absorbance line width and intensity increased, consistent with the transition from intramolecular to intermolecular hydrogen bond formation involving salicylic OH and DMSO. These protons exist in a relatively

available non-bonded state or a weak intramolecular hydrogen bonded state in the absence of Lewis base.

The marked ν_aCOO and salicylate OH IR shifts observed with a molar concentration ratio for $Zn^{II}(3,5\text{-DIPS})_2$: Lewis base of 1 : 1 (figure 4) are consistent with stronger bonding of the first molecule of DMSO to $Zn^{II}(3,5\text{-DIPS})_2$ and a less strongly bonded second DMSO to form $Zn^{II}(3,5\text{-DIPS})_2(DMSO)_2$. A further smaller increase in IR absorption associated with addition of two additional equivalents of Lewis base supports formation of $Zn^{II}(3,5\text{-DIPS})_2(\text{Lewis base})_4$, with two molecules of Lewis base involved in intermolecular hydrogen bonds.

There was a concomitant increase of a new absorption band at 1012 cm^{-1} (figure 6) due to axial bonding of DMSO to Zn^{II}, consistent with an earlier report [23] and a role of DMSO in weakening carboxylate and salicylic OH interaction with Zn^{II}. The shift in absorbance for salicylate OH groups from 3240 cm^{-1} to 3100 cm^{-1} is consistent with weakening of bonding of salicylic OH to Zn^{II} and a strengthening of intramolecular hydrogen bond with addition of more DMSO. Maximum shifts for both functional groups were achieved at a molar concentration ratio for DMSO : $Zn^{II}(3,5\text{-DIPS})_2$ of 2 : 1 (figure 4).

The addition of DMSO to $Zn^{II}(3,5\text{-DIPS})_2$ also resulted in new bands for sulfoxide stretching frequencies at 1070 for free DMSO and at 1012 cm^{-1} for axially bonded DMSO and intermolecularly hydrogen bonded DMSO, as shown in figure 4. The increase in absorbance at these two frequencies is shown in figure 6.

These plots and spectra reveal stronger bonding of DMSO to Zn^{II} with addition of two equivalents of DMSO and subsequent weaker bonding due to intermolecular hydrogen bond formation. Similarly, increasing additions of DMSO to a non-polar solution of 3,5-DIPS acid revealed a clear increase in absorption at 1019 cm^{-1} for intermolecular hydrogen bonding. These results show that for a molar concentration

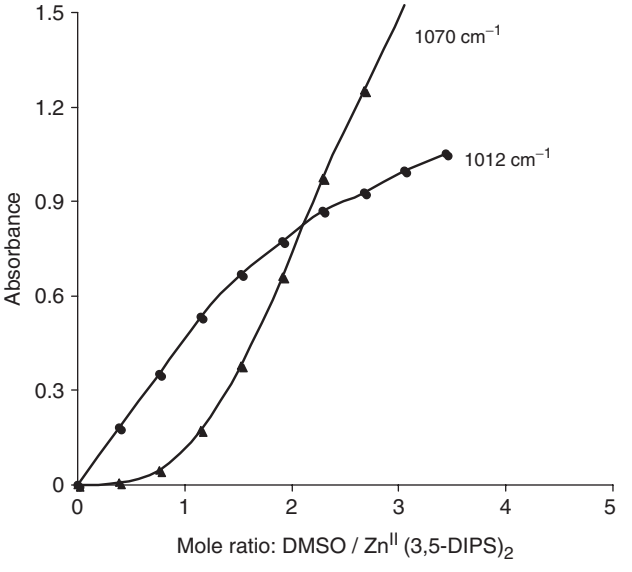


Figure 6. Absorbances at 1070 and 1012 cm^{-1} in FTIR spectra at 24°C for 0.0369 M CCl_4 solutions of $Zn^{II}(3,5\text{-DIPS})_2$ containing varying DMSO : $Zn^{II}(3,5\text{-DIPS})_2$ mole ratios.

ratio of DMSO : Zn^{II}(3,5-DIPS)$_2$ > 2, intramolecular hydrogen bonding decreases as a result of intermolecular hydrogen bond formation between protons of salicylic OH groups of 3,5-DIPS ligands in Zn^{II}(3,5-DIPS)$_2$ and oxygen atom of DMSO.

These results support conclusions based upon NMR spectra showing that addition of DMSO to a $CDCl_3$ solution of Zn^{II}(3,5-DIPS)$_2$ initially result in axial bonding of two molecules of DMSO to the Zn^{II}. IR absorption of salicylic OH groups of Zn^{II}(3,5-DIPS)$_2$ shows initial bonding of DMSO involves axial bonding to the Zn^{II} atom, resulting in formation of intramolecular hydrogen bonds between protons of salicylic OH and 3,5-DIPS carboxylate groups.

Addition of EA as the Lewis base to a CCl_4 solution of Zn^{II}(3,5-DIPS)$_2$ weakens interactions between carboxylate and salicylic OH. This weakening was less marked than with DMSO. The initial change following addition of two equivalents of EA was a small frequency shift for asymmetric vibrations of the carboxylate groups, ν_aCOO, from 1560 cm^{-1} to 1567 cm^{-1} and a corresponding small shift to lower frequency for salicylic OH groups from 3238 cm^{-1} to 3219 cm^{-1} with initiation of intramolecular hydrogen bonds. With addition of three more equivalents of EA there was a further slight shift in frequency for absorption of the ν_aCOO from 1567 cm^{-1} to 1570 cm^{-1} with a corresponding modest increase in frequency shift for the salicylic OH group from 3220 cm^{-1} to 3212 cm^{-1}. There was a concomitant increase in intensity for salicylic OH at 3200 cm^{-1}, which increased with increasing addition of EA.

The maximum increase in FTIR absorbance was observed at a higher mole ratio of EA : Zn^{II}(3,5-DIPS)$_2$ due to the weaker basicity of EA compared to DMSO and a smaller change in dipole moment for the salicylic OH caused by EA. These results are in full accordance with NMR shift data obtained for EA.

A distinctive influence on the characteristic absorption frequency for salicylic OH groups (figure 4) and on the frequency for asymmetric stretching of carboxylate groups for 3,5-DIPS ligands was also observed following successive additions of EA. The maximum NMR chemical shift for salicylic OH groups was also obtained at molar concentration ratio, EA : Zn^{II}(3,5-DIPS)$_2 \geq 5$.

IR spectra following successive additions of EA through the range of 1800 to 1500 cm^{-1} and plots of the increase in absorbance at 1741 cm^{-1} for ν_aCO and 1708 cm^{-1} for ν_sCO of non-bonded free carbonyl of EA (figure 7) show the shift from 1560 cm^{-1} for Zn^{II}(3,5-DIPS)$_2$ to 1570 cm^{-1} for Zn^{II}(3,5-DIPS)$_2$(EA)$_4$ following addition of five equivalents of EA with initial axial bonding of two equivalents of EA to Zn^{II}. Because EA is a weak base, the stiochiometry required for complete saturation of the axial and hydrogen bonding sites of Zn^{II}(3,5-DIPS)$_2$ to yield Zn^{II}(3,5-DIPS)$_2$(EA)$_2$ and Zn^{II}(3,5-DIPS)$_2$(EA)$_4$ exceeds the anticipated molar ratio of four for EA to produce complete axial and intermolecular hydrogen bond formation.

Absorptions for ν_aCOO stretch of 3,5-DIPS ligands at 1560 cm^{-1} also undergo a weak change in intensity along with a modest shift to 1570 cm^{-1} upon addition of five equivalents of EA to CCl_4 solutions of Zn^{II}(3,5-DIPS)$_2$ to form Zn^{II}(3,5-DIPS)$_2$(EA)$_4$, suggesting that, due to low basicity of EA, axial bonding of EA with Zn^{II}, unlike DMSO, is accompanied by weakening of bonds between oxygen of carboxylate and salicylic OH. Thus, to achieve intramolecular hydrogen bond formation involving salicylic OH groups of 3,5-DIPS ligands in the presence of EA requires a higher concentration of EA compared to DMSO to achieve complete equilibrium, as illustrated in scheme 1.

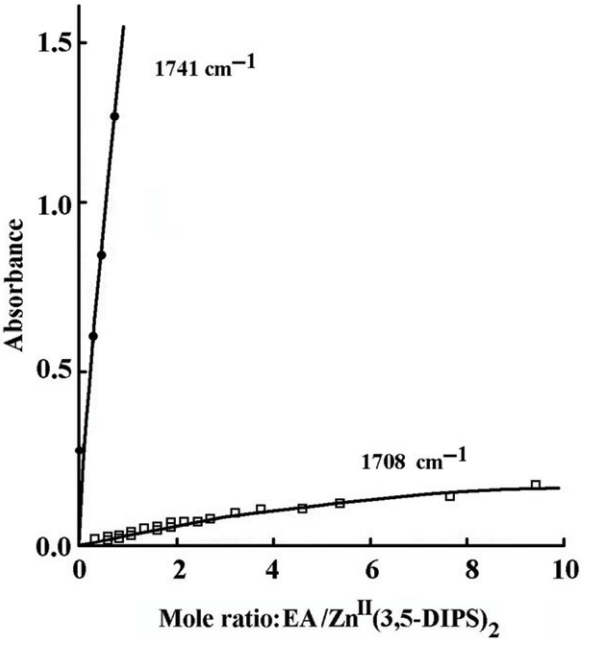


Figure 7. Absorbances at 1741 and 1708 cm^{-1} in FTIR spectra at 24°C for 0.0369 M Zn^{II} (3,5-DIPS)$_2$ CCl_4 solutions containing varying EA : Zn^{II}(3,5-DIPS)$_2$ mole ratios.

The sequence of EA bonding to Zn^{II}(3,5-DIPS)$_2$ is the same as the sequence observed for DMSO bonding with Zn^{II}(3,5-DIPS)$_2$, however, bonding interactions of EA are weaker (figure 7). These results support results reported previously [20] showing a regular increase in magnitude for $\Delta\nu = (\nu_a COO–\nu_s COO)$ for Zn^{II}(3,5-DIPS)$_2$(L)$_n$ with increasing of basicity of axial ligands, L, such as H_2O (150 cm^{-1}), DMSO (165 cm^{-1}), NC (168 cm^{-1}), and phenanthroline (172 cm^{-1}).

4. Conclusions

Using NMR and FTIR existing bonds between carboxylate and salicylic OH oxygens and Zn^{II} in non-polar solutions of Zn^{II}(3,5-DIPS)$_2$ are initially weakened by the bonding of two equivalents of DMSO or EA resulting in concomitant strengthening of intramolecular hydrogen bonds from carboxylate oxygens with protons of salicylic OH in Zn^{II}(3,5-DIPS)$_2$. Ternary complexes Zn^{II}(3,5-DIPS)$_2L_2$, in which the ligands are axially coordinated to Zn^{II}, are formed. Addition of more equivalents of Lewis base resulted in weakening of intramolecular hydrogen bonding and strengthening of intermolecular hydrogen bonds between the salicylic OH protons with the Lewis base, giving solvated complexes, Zn^{II}(3,5-DIPS)$_2L_4$.

The stronger Lewis basicity of DMSO accounts for observations that equilibrium constants, K_{eq}, for DMSO are larger than for EA in Zn^{II}(3,5-DIPS)$_2$ (Lewis base) complex formations. These results are consistent with small values found for changes in standard entropy and enthalpy for the overall bonding processes between Lewis bases with Zn^{II}(3,5-DIPS)$_2$, which were anticipated to be dependent upon the nature of the

metallochelate and the suggested sequential multistage mechanisms of bonding interactions.

These results allow understanding of antiperoxyl radical reactivity and decrease in this reactivity in the presence of Lewis bases revealed earlier for Zn^{II}, Cu^{II}, and Fe^{III} 3,5-DIPS chelates [4, 6, 7]. At comparatively small concentrations of Lewis base the decrease of antiperoxiradical reactivity is due to axial coordination. At the higher concentrations of Lewis base the decrease of antiperoxyl radical reactivity of these chelates is due to intermolecular hydrogen bonding between the salicylic OH protons with the Lewis base.

Acknowledgements

NMR studies were supported by the NFSAT (Armenia) fund (Grant LTTG 2003/06) and FTIR studies were supported by ANSEF (US) fund (grant) and the Armenian Ministry of Science and Education (Grant N 1-22-1292). We thank Essential Metalloelement Analyses Laboratory (USA), and Dr. Garik Martirosyan, Dr. Alexander Schahchatuni, and Dr Henrik Panosyan, Molecular Structure Research Center NAS of Armenia, for their practical assistance.

References

[1] J.R.J. Sorenson, L.S.F. Soderberg, L.W. Chang, W.M. Willingham, M.L. Baker, J.B. Barnett, H. Salari, K. Bond. *Eur. J. Med. Chem.*, **28**, 221 (1993).
[2] G. Morgant, B. Viossat, J.C. Daran, M. Roch-Arveiller, J.P. Giround, N.H. Dung, J.R.J. Sorenson. *J. Inorg. Biochem.*, **70**, 137 (1998).
[3] J.R.J. Sorenson. *Current Med. Chem.*, **9**, 1867 (2002).
[4] L.A. Tavadyan. *Chem. J. Armenia*, **60**, 602 (2007) (in Russian).
[5] P. Lemoine, B. Viossat, N.H. Dung, A. Tomas, G. Morgant, F.T. Greenaway, J.R.J. Sorenson. *J. Inorg. Biochem.*, **98**, 1734 (2004).
[6] L.A. Tavadyan, H.G. Tonikyan, S.H. Minasyan, L.A. Harutyunyan, F.T. Greenaway, J.R.J. Sorenson. *Inorg. Chim. Acta*, **328**, 1 (2002).
[7] L.A. Tavadyan, G.Z. Sedrakyan, S.H. Minasyan, F.T. Greenaway, J.R.J. Sorenson. *Transition Met. Chem.*, **29**, 684 (2004).
[8] L.A. Tavadyan, V.A. Mardoyan, A.B. Nalbandyan. *Chem. Phys.*, **5**, 1377, (1986) (in Russian).
[9] I.R.C. Barclay, C.E. Edwards, M.R. Vinqvist. *J. Am. Chem. Soc.*, **121**, 6226 (1999).
[10] D.V. Avila, K.U. Ingold, J. Lusztuk. *J. Am. Chem. Soc.*, **117**, 2929 (1995).
[11] L.A. Tavadyan, V.A. Mardoyan, A.B. Nalbandyan. *Chem. Phys.*, **4**, 1107, (1985) (in Russian).
[12] L. Valgimigli, J.T. Banks, K.U. Ingold, J. Lusztyk. *J. Am. Chem. Soc.*, **117**, 9966 (1995).
[13] M.I. de Heer, P. Mulder, H.G. Korth, K.U. Ingold, J. Lusztyk. *J. Am. Chem. Soc.*, **122**, 2355 (2000).
[14] J. Palomar, J.L.G. De Paz, J. Catalan. *J. Phys. Chem., A*, **104**, 6453 (2000).
[15] A.J. Gordon, R.A Ford. *The Chemist's Companion*, John Wiley Sons, New York (1972).
[16] R.J. Hore. *Nuclear Magnetic Resonance*, Oxford University Press, Oxford (1998).
[17] N.M. Emanuel, G.B. Sergeev. *Experimental Methods of Chemical Kinetics*, Mir, Moscow (1980) (in Russian).
[18] R.S. Drago. *Physical Methods in Chemistry*, W.B. Saunders Company, Mir, Moscow, p. 19 (Russian translation) (1981).
[19] F.L. Slejko, R.S. Drago, D.G. Brown. *J. Am. Chem. Soc.*, **94**, 9210 (1972).
[20] P. Lemoine, B. Viossat, N.H. Dung, A. Tomas, G. Morgant, F.T. Greenaway, J.R.J. Sorenson. *J. Inorg. Biochem.*, **70**, 137 (1998).
[21] I.A. Koppel, V.A. Palm. *Linear Free-Energy Relationships*, N.B. Chapman, J. Shorter (Eds), Chap. 5, Vol. 204, pp. 203–280, Plenum Press, London (1972).
[22] J. Catalan, J. Palomar, C. Diaz, J.L.G. De Paz. *J. Phys. Chem., A*, **101**, 5183 (1997).
[23] F.T. Greenaway, L.J. Norris, J.R.J. Sorenson. *Inorg. Chim. Acta*, **145**, 279 (1988).